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SYNOPSIS Soil reinforcement with randomly oriented, individual synthetic fibers has been applied to laboratory specimens of a compacted cohesive soil. Fiber contents of up to 1.0 % by soil dry weight were mixed with the soil. Data from unconfined compression (static) testing and resilient modulus (dynamic) testing have been presented. Experimental work showed that the fibers increased the soil unconfined compressive strength, ductility, toughness, static and dynamic energy absorption capacities, the resilient strain and the number of cycles to failure. The soil resilient modulus and the permanent strain both decreased with the increase in fiber content.

INTRODUCTION

Soil reinforcement has increasingly become a viable option for improving the performance of earth structures under seismic and dynamic loading. A variety of soil reinforcement techniques have been developed in the past two decades; during which the use of geosynthetics has increased significantly. Such techniques include, for example, mechanically stabilized earth (MSE) slopes and walls. The MSE systems normally consist of continuous reinforcement members (geotextiles, geogrids or metal straps) placed in layers to carry the designed load through the soil-to-reinforcement adhesion. The success of applying these systems in many field applications has been associated with a high cost resulting from a conservative design approach. Further discussions and case histories on the merits of the MSE systems can be found in the literature (Al-Wahab and Al-Qurna, 1995; Bonaparte et al., 1987; Freitag, 1986; Maher and Gray, 1990; and Richardson and Behr, 1988).

This study deals with a different kind of earth reinforcement: mixing individual geosynthetic fibers with the soil. The fibers would be randomly oriented and uniformly distributed in the soil mass. A review of literature indicated that very few technical studies have been conducted in this area (Al-Qurna, 1990; Crockford et al., 1993, El-Kedra, 1990; Freitag, 1986; Gray and Al Refeai, 1986; Gray and Ohashi, 1983; Hoare, 1977; Maher, 1988; and McGown et al., 1985). Except for Maher (1988), these studies were focused on the static strength properties of fiber-reinforced soils. Maher (1988) studied both the static and dynamic behavior of fiber-reinforced sands.

In this study, a fiber-reinforced compacted cohesive soil was tested in unconfined compression (static) and resilient (cyclic) loading conditions. Collated fibrillated polypropylene fibers were used. Experimental results presented include the unconfined compressive stress-strain curves, and relationships between the fiber content (percent of soil dry weight) and the soil compressive strength, ductility, toughness, static and dynamic energy absorption capacities, resilient and permanent strains, resilient modulus and the number of cycles to failure.

EXPERIMENTAL PROCEDURE

Materials

This study used a silty-clay-loam (AASHTO Classification A-4) with a 2.71 specific gravity , 22.2 % clay, 73.9 % silt, 3.9 % sand (AASHTO T 88-93), 33.8 % liquid limit (AASHTO T 89-93), 8.5 % plasticity index (AASHTO T 90-92), 16.38 kN/m^3 (104.3 pcf) standard dry density and an optimum moisture content (OMC) of 18.5 % (AASHTO T 99-93 Method A). The soil was taken from a fill material used on a county road in Illinois, where a 76.2-m (250-ft) test section with fiber-reinforced fill was also constructed.

The reinforcing fibers used in this study were collected, fibrillated, polypropylene fiber bundles 25.4 mm (1 in.) long, consisting of 10 to 15 individual fibers interconnected by cross fibrils. The fiber bundles are designed to open into individual fibers when mixed with a course granular material such as sand or gravel. The average physical and mechanical properties of the polypropylene material making up these fibers are summarized in Table 1 below.

Table 1. Mechanical and physical properties of the polypropylene fibers used in this study. (Data from Synthetic Industries, 1994).

Tensile Strength	310 MPa (45 ksi)
Secant Elastic Modulus	4826 MPa (700 psi)
Tensile Strain	15 %
Specific Gravity	0.91
Melting Point	170 ± 5 ^{o}C (338 ± 9 ^{o}F)

Sample Preparation

The fiber-reinforced soil samples were prepared by pre-opening the fiber bundles, mixing the soil with fibers and compacting the mix into cylinders. These procedures are described below.

Pre-Opening the Fiber Bundles

Mixing observations showed that the fiber bundles do not open into individual fibers when mixed with a cohesive soil. Therefore, a dry sand with approximately 60 % passing the US #30 sieve and 40 % passing the US #40 sieve was used for pre-opening the bundles before incorporating them into the soil under study. About 2.5 kg (5.5 lb) of the dry sand, 125 g of water and 25 g of fiber bundles were mixed together using a Lancaster counter current batch mixer. Mixing continued, with the drum down, for approximately 20 minutes. This was a successful procedure for opening most of the fiber bundles into individual fibers, leaving only a small percentage of the fiber bundles not fully opened. The opened fiber bundles (thereafter, will be referred to as fibers) were separated from the sand by flooding the mix with water, agitating the mix by hand and recovering the floating fibers. The process was repeated until all fibers were separated from the sand and recovered. The fibers were placed in a 110^{o}C (230 ^{o}F) oven for 12 to 15 hours until dry.

Soil-Fiber Mixing

The pre-opening and drying procedure produced a large cluster of dry, slightly dusty, fibers which were easier to disperse as individual fibers into the soil , than the fiber bundles. A Lancaster counter current batch mixer was used for mixing the soil with compaction water and the pre-opened fibers. The soil was first mixed with the compaction water, followed by a gradual addition of the fibers to the moist soil as mixing continued. Difficulties with mechanical mixing included fiber balling, sticking into small soil clods, and non-uniform distribution throughout the soil. These difficulties significantly increased with the increase in fiber content beyond 0.2 %. The fiber content (f) is defined as the weight of fibers expressed as a percentage of the soil dry weight. The soil-fiber mix was sealed in the mixer pan using an airtight bag and let sit for 16 hours to ensure a uniform distribution of moisture.

Preparation of Test Specimens

The soil-fiber mixture was compacted in three equal layers into a 50.8-mm diameter x 101.6 mm-high (2-in. x 4-in.) mold using a manually operated rammer weighing 1.81 kg (4 lb) with a drop of 304.8 mm (12 in.). All specimens were compacted at an average dry density (γ_d) of 16.19 kN/m^3 (103.1 pcf) and an average moisture content (MC) of 18.2 %, respectively; close to the maximum dry densities and OMCs of the soil at different fiber contents. The number of blows required to achieve the average density increased with the increase in fiber content (f). At each fiber content, three compacted cylindrical specimens were prepared; one was used for unconfined compressive testing, one for resilient modulus testing, and one was used as a backup specimen for repeating either test as needed. The compacted specimens were extruded from the mold using a hydraulic sample extruder and were immediately sealed in an airtight plastic bag to be ready for testing later on the same day. At fiber contents of 0.4 % and more, the mechanical mixing method did not produce a uniform fiber distribution. In these cases, additional hand mixing was necessary to ensure as uniform fiber distribution as possible. Also, during compaction, fibers were observed to accumulate between the compacted layers. To avoid this problem, the additional hand mixing was followed by squeezing the soil-fiber mix for each layer prior to placement in the mold.

TESTING PROCEDURES

Unconfined Compression Test

Unconfined compression tests were conducted on the fiber-reinforced soil specimens, with 0 %, 0.2 %, 0.4 %, 0.7 % and 1.0 % fiber contents, in accordance with AASHTO T 208-92.

Resilient Modulus Test

Resilient modulus testing was conducted on soil specimens with 0 %, 0.2 %, 0.4 %, 0.7 %, and 1.0 % fibers. The testing apparatus shown on Figure 1 was used in this study. The test procedure described by Thompson and Robnett (1976) was also followed in this study. Essentially, the test was conducted on the fiber-reinforced soil specimens in a manner similar to that mentioned in AASHTO T 292-91 for cohesive soils except that: 1) A load duration of 0.060 seconds with a rectangular wave form, a relaxation period of 3 seconds, and a cycle duration of 30 seconds (10 cycles @ 3 sec. per cycle) were used in this test, 2) No confining pressure was applied (unconfined test), 3) A surge tank was

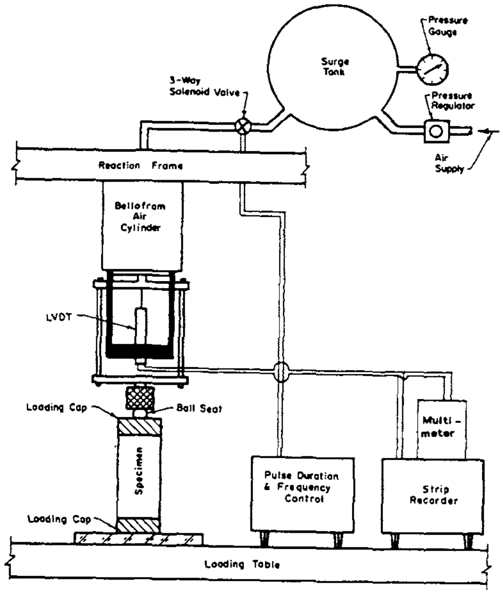

Figure 1. Resilient Modulus Testing Apparatus.

used to provide a constant source of air pressure (± 0.67 kPa (± 0.1 psi)). The applied axial stress (σ_a) was a function of the surge tank pressure gage reading calibrated with an electronic load cell, 4) One Linear Variable Differential Transducer (LVDT) mounted externally was used (in lieu of two). Also, a digital multimeter was connected to the LVDT in parallel with the strip recorder for continuous measurement of the changes in specimen height during the test, 5) Conditioning was done by applying 100 cycles of an applied axial stress (σ_a) of 45.8 kPa (6.6 psi) instead of the recommended 1000 cycles, 6) Testing was performed following the loading sequence in Table 2. The maximum applied axial stress 438.9 kPa (63.7 psi) was governed by the surge tank gage capacity, and 7) The tests were terminated either at the end of the loading sequence or when the samples failed (physically or by reaching 15 % axial strain), whichever occurred first. Samples that did not fail at the maximum load were also subjected to more load cycles up to 1000.

Due to equipment limitations, the LVDT position was reset during the test to allow for increased sample deformations at high loads. LVDT resetting took approximately 25 seconds which did not affect the accuracy of the test. A strip chart recorder was used to measure the resilient and permanent deflections per load cycle (Δ_{rcy} and Δ_{pcy}) throughout the test, as shown on Figure 2. Knowing that the average resilient strain per load cycle (ε_{rcy}) is (Δ_{rcy}) divided by the initial specimen height, at any load increment, the resilient modulus (E_r) was calculated as the axial stress (σ_1) divided by (ε_{rcy}). The axial stress (σ_1) was adjusted for the changes in the specimen cross-sectional area resulting from the permanent strains in the specimen.

Table 2. Loading Sequence in Resilient Modulus Test.

Sequence Number	Applied Axial Stress, σ_a, kPa	Load Applications Per Test Cycle, N
Preconditioning	45.8	100
1	16.3	10
2	31.5	10
3	45.8	10
4	60.1	10
5	87.7	10
6	118.7	10
7	148.8	10
8	178.8	10
9	207.9	10
10	236.9	10
11	265.5	10
12	293.6	10
13	323.2	10
14	351.7	10
15	380.8	10
16	409.9	10
17	438.9	10
18	438.9	To Failure

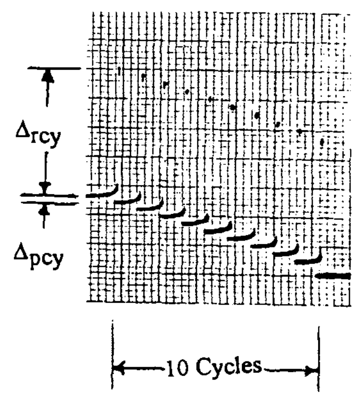

Figure 2. Typical Strip Chart Output From Recorder During a Resilient Modulus Test.

EXPERIMENTAL RESULTS

Static Data

Unconfined Compressive Strength and Stress-Strain Curves

The effects of fiber content (f) on the unconfined compressive strength (σ_u) is shown on Figure 3, in which (σ_u) increased with the increase in (f). A large data scatter is seen on this figure. The authors believe that the main reason,

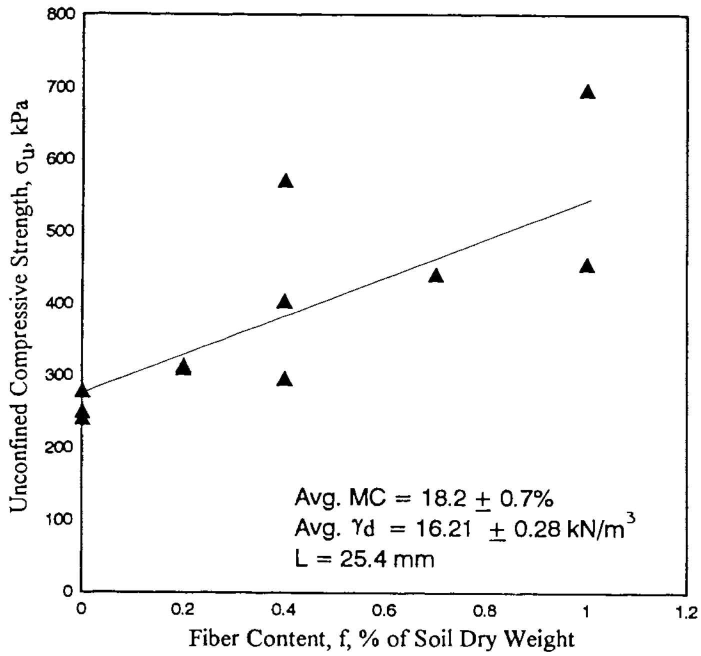

Figure 3. Effect of Fiber Content on the Unconfined Compressive Strength of a Compacted Cohesive Soil.

among others, for the scatter was the variation in quality of fiber distribution and mix homogeneity from one sample to another. Slight moisture variations could also have contributed to the data scatter. Previous studies (Al-Qurna, 1990; and El-Kedrah, 1990) showed that fibers have little effect on the maximum dry density and OMC. However, the studies showed that compaction moisture has a significant effect on the strength (σ_u) of fiber-reinforced soils. Also, these studies showed that, for each soil, there appeared to be an "optimum" fiber content which maximized the soil strength. For the range of fiber contents and the soil type in this study, no such optimum was concluded. Figure 4 shows the stress-strain curves for specimens with 0.0 %, 0.7 %, and 1.0 % fibers. This figure indicates that fibers increased the ductility, the energy absorption capacity (EAC) and the soil toughness (T).

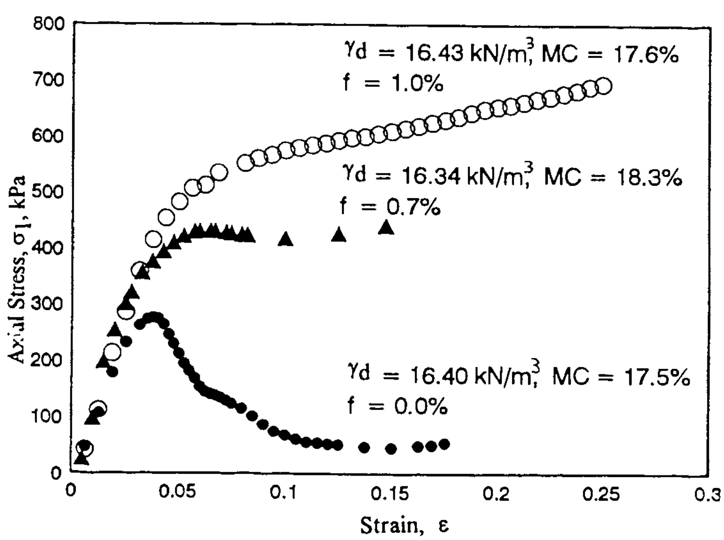

Figure 4. Effect of Fiber Content on the Unconfined Compressive Stress-Strain Curves for a Compacted Cohesive Soil.

The ductility was defined as the initial yield strain (ε_y), normally observed at the end of the straight line portion of the stress-strain curve. At fiber contents below 0.7 %, where a peak failure stress was observed, ductility corresponded to the strain at failure. The EAC was defined as the area under the stress-strain curve from 0 to $3\varepsilon_y$. The soil toughness (T) at any fiber content was defined as the EAC divided by the area under the stress-strain curve from 0 to ε for the same soil. Toughness and EAC are important indicators of the soil behavior under dynamic or seismic loading. A static energy ratio (ER_S) was defined as the EAC at any fiber content (f) divided by the EAC at f = 0% (plain soil). Figure 5 shows the effect of fiber content on the values of (ER_S) and (T). By definition, the ER_S for the plain soil (f = 0%) equals 1.0. Also, by definition, toughness primarily depends on the shape of the stress-strain curve for that soil. Therefore, for an elastoplastic soil, the maximum value of (T) is 3. As the fiber content increased from 0 % to 1 %, the ER_S values increased by approximately 6 times. At fiber contents higher than 0.2%, the toughness exceeds 3 thereby indicating a strain-hardening behavior.

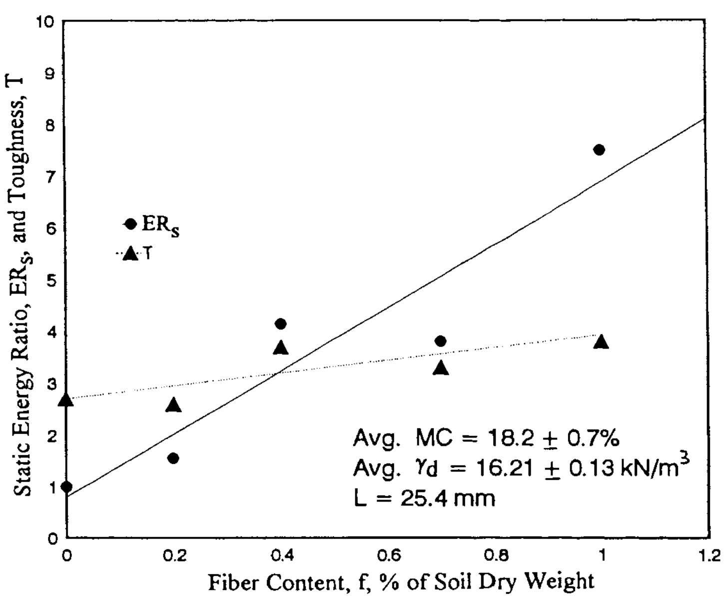

Figure 5. Effect of Fiber Content on the Energy Ratio and Toughness of a Compacted Cohesive Soil.

Dynamic Data

Soil Resilient Modulus

The resilient modulus (E_r) of a soil varies with the axial stress (σ_1). Figure 6 shows a typical stress versus strain curve of a soil specimen in a resilient modulus test. Figure 7 shows typical E_r versus (σ_1) relationships for the soil at 0 %, 0.2 %, and 0.7 % fiber contents.

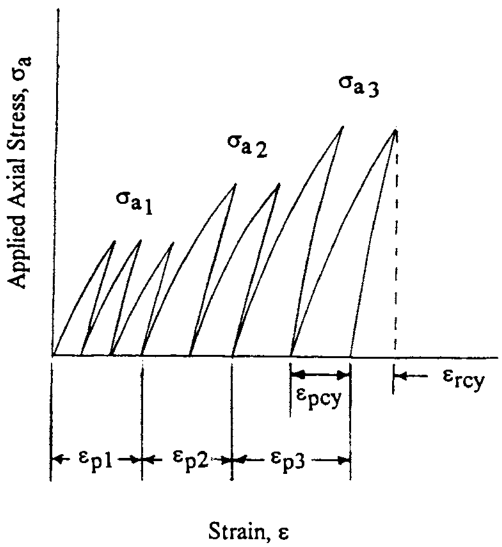

Figure 6. A Typical Stress-Strain Relationship for the Soil in Resilient Modulus Testing.

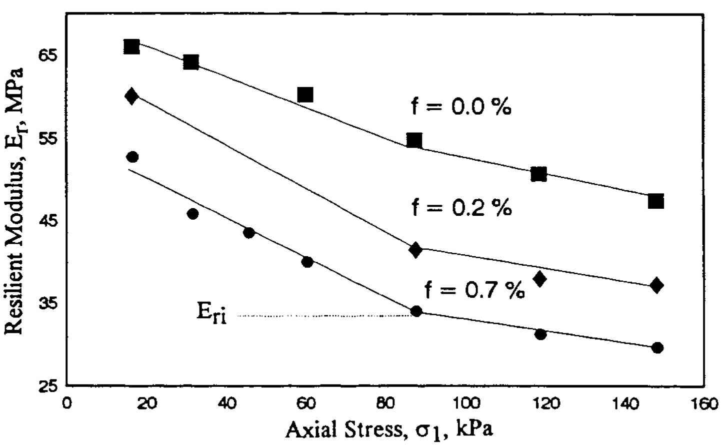

Figure 7. Typical Resilient Modulus vs. Applied Axial Stress.

The value of (E_{ri}) at or near the break point on the (E_r) versus (σ_1) curve (Figure 7) is sometimes used in pavement design. For the plain and fiber-reinforced soil specimens in this study, the break points occurred at an axial stress (σ_1) of approximately 87 kPa (12.6 psi). These (E_{ri}) values are plotted versus the fiber content (f) on Figure 8. As in the static testing, the data scatter shown on this figure was primarily due to the variation in quality of fiber distribution from one sample to another and, possibly, to slight variations in moisture and test conditions. The trend on Figure 8 indicates that (E_{ri}) decreases with the increase in (f). Field test results from falling weight deflectometer (FWD) on a test section in Illinois with fiber-reinforced subgrade fill (at f = 0.2 %) showed that the E_{ri} values were 39.3 MPa (5.7 ksi) for the control section (f = 0 %) and 37.2 MPa (5.4 ksi) for the test section (f = 0.2 %). Grogan and Johnson (1994) reported that the E_{ri} data from FWD tests on their experimental sections with fiber-reinforced soils were inconclusive. To explain this behavior, the resilient strain per cycle (ε_{rcy}) is plotted versus (f) on Figure 9 for different stress levels. This figure shows that (ε_{rcy}) increases with the increase in (f). And, since $E_r = \sigma_1/\varepsilon_r$, the value of E_r would decrease when (ε_r) increases at a constant (σ_1) value. The addition of fibers to the soil appears to increase the soil's "spring back" ability (or resiliency) and reduce the amount of permanent strain. In the mean time, the increase in (ε_{rcy}) with (f) at a given (σ_1) indicates that the amount of elastic strain energy per cycle (ie. 0.5 x σ_1 x ε_{rcy}) increases with the increase in fiber content. Therefore, a dynamic energy ratio (ER_d), defined as the ratio of (ε_{rcy}) at any (f) to (ε_{rcy}) at f = 0 %, was introduced for comparison with the (ER_s) as previously defined. The (ER_d) values at different stress levels, plotted on Figure 10, increased by 2 times as (f) was increased from 0 % to 1 %. Knowing that ER_s varied by approximately 6 times, the ratio of ER_s to ER_d appears to be in the order of 3 to 1 for this soil. Such a relationship might help in back calculating the E_{ri} from ER_s without conducting the resilient testing. Note that the data scatter on Figure 10 also increases with the increase in (f), and the increase in fiber content was associated with a decrease in homogeneity of the soil-fiber mix. The decrease in (E_{ri}) with (f) would not encourage pavement designers to

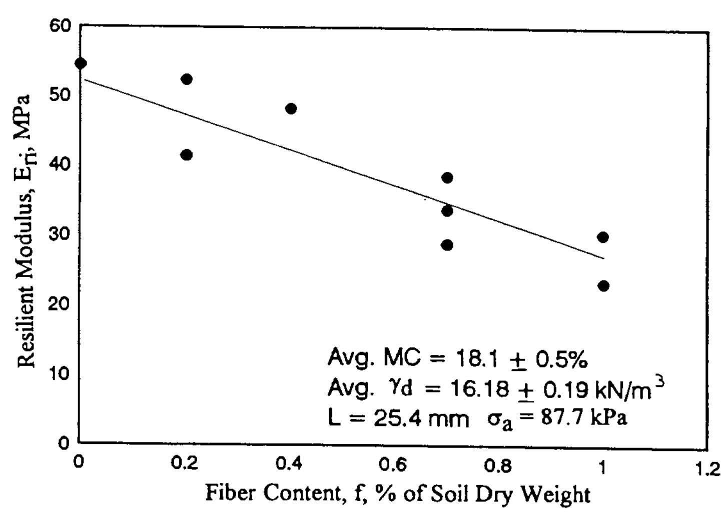

Figure 8. Resilient Modulus (E_{ri}) vs. Fiber Content.

consider the use of fibers alone in subgrades (without cementitious admixtures such as lime or cement). However, considering the other benefits, it appears that the use of fibers would be most desirable in earth structures subject to seismic and dynamic loading.

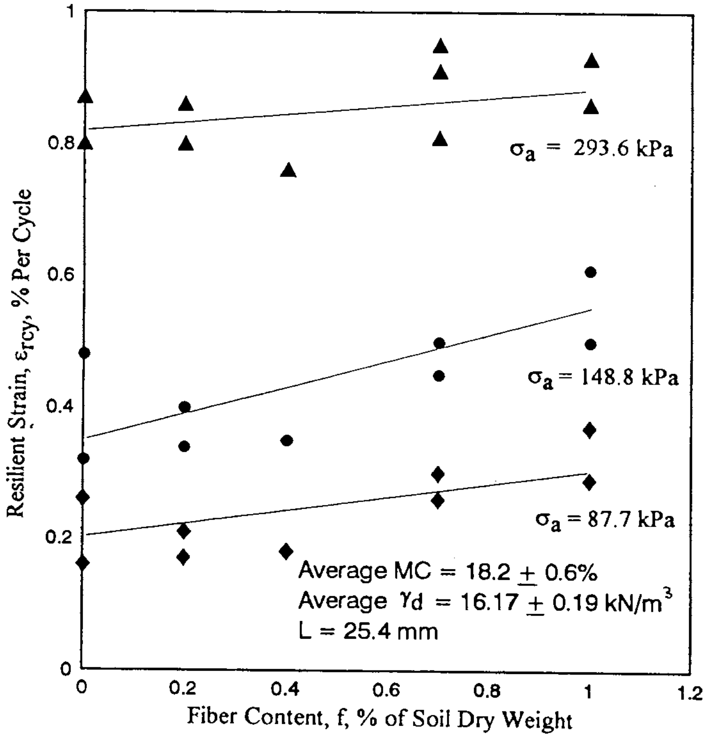

Figure 9. Resilient Strain Per Cycle vs. Fiber Content at Different Stress Levels.

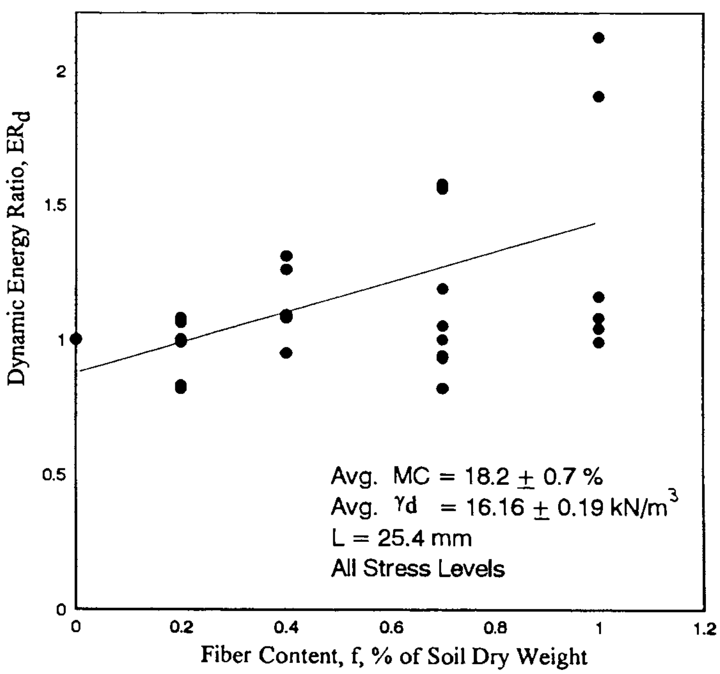

Figure 10. Effect of Fiber Content on the Dynamic Energy Ratio at Different Stress Levels.

Permanent Strain under Cyclic Loading

Figure 6 illustrates the definition of a cumulative permanent strain (ε_{cp}) as the sum of all permanent strains (ε_{p1}, ε_{p2}, ε_{p3}, etc.) resulting from all load cycles up to the maximum applied stress level. Also, the permanent strain per cycle (ε_{pcy}) at any stress level was defined as the permanent strain, at that stress, divided by the number (N) of load cycles (N = 10 unless otherwise specified herein). Both values of ε_{cp} (up to σ_1 = 438.9 kPa) and ε_{pcy} (at σ_1 = 438.9 kPa) are plotted versus (f) on Figure 11. This figure shows that fibers reduce both (ε_{pcy}) and (ε_{cp}) under cyclic loading. Since the total strain in each cycle equals (ε_{rcy} + ε_{pcy}), the decrease in (ε_{pcy}) with (f) on Figure 11 is consistent with the increase in (ε_{rcy}) with (f) on Figure 9. And, because the same behavior was observed at all other stress levels, where (ε_{pcy}) decreased with (f), the cumulative permanent strain (ε_{cp}) also decreased with (f). The number of load cycles (N) to failure are plotted versus (ε_{cp}) at different fiber contents on Figure 12. At f = 0.4 %, about 250 cycles were needed to reach failure, compared to 150 cycles at f = 0 %. Also, at f = 0 % failure occurred at a stress level (σ_a) of 380.8 kPa. At f = 0.2 %, 0.4 % and 0.7 %, failure occurred at σ_a = 438.9 kPa. The sample with 1% fibers did not fail even after nearly 1000 cycles.

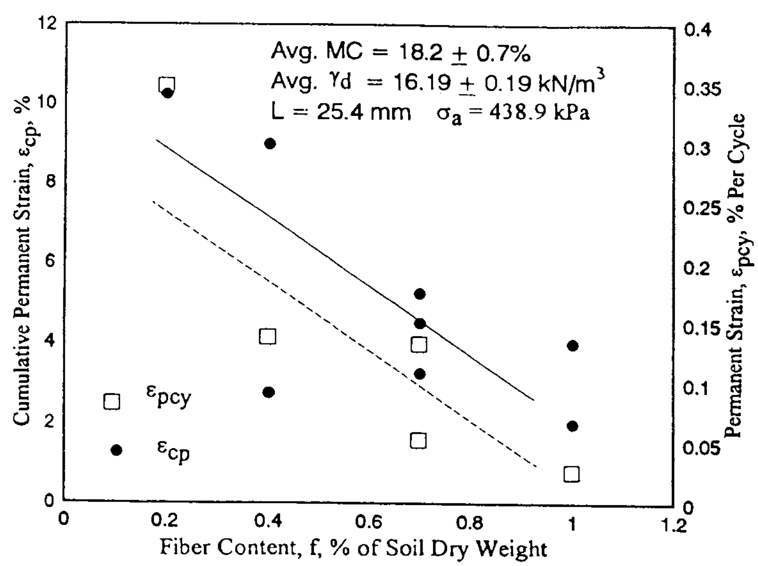

Figure 11. Cumulative Permanent Strain vs. Fiber Content (Note: At f = 0 %, the specimen failed prior to σ_1 = 438.9 kPa).

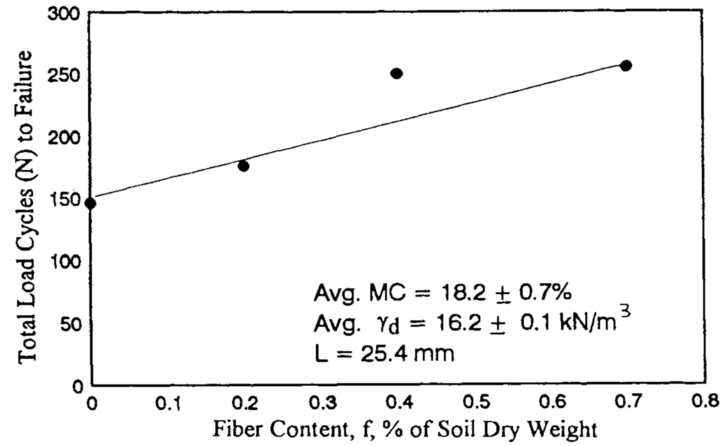

Figure 12. Effects of Fiber Content on the Number of Load Cycles Accumulated Prior to Specimen Failure.

CONCLUSIONS

1. The use of randomly oriented, individual polypropylene fibers in a compacted cohesive soil increased the soil unconfined compressive strength, ductility, toughness, static and dynamic energy absorption capacities, the resilient strain and the number of cycles to failure.

2. The fibers reduced the soil resilient modulus (due to increase in resilient strain) and the permanent strain.

3. Based on the findings in (1) above, it appears that fibers would be most beneficial when used in earth structures subject to seismic or dynamic loading. However, since fibers reduced the soil resilient modulus in this study, the use of fibers alone in subgrade soils may not be beneficial from a pavement design standpoint. The authors recommend that further studies be conducted to better characterize the dynamic behavior of fiber-reinforced soils.

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